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Abstract

NASA and Japan's Institute of Space and Astronautical Science (ISAS) have agreed to cooperate on the first mission to collect samples from the surface of an asteroid and return them to Earth for in-depth study. The MUSES-C mission will be launched on a Japanese MV launch vehicle in January 2002 from Kagoshima Space Center, Japan, toward a touchdown on the asteroid Nereus in September 2003. A NASA-provided miniature rover will conduct in-situ measurements on the surface. The asteroid samples will be returned to Earth by MUSES-C via a parachute-borne recovery capsule in January 2006.

NASA and ISAS will cooperate on several aspects of the mission, including mission support and scientific analysis. In addition to providing the rover, NASA will arrange for the testing of the MUSES-C re-entry heat shield at NASA/Ames Research Center, provide supplemental Deep Space Network tracking of the spacecraft, assist in navigating the spacecraft and provide arrangements for the recovery of the sample capsule at a landing site in the U. S. Scientific co-investigators from the U. S. and Japan will share data from the instruments on the rover and the spacecraft. They will also collaborate on the investigations of the returned samples. The MUSES C spacecraft will carry a camera, LIDAR, an IR spectrometer, an X-ray spectrometer and the sample acquisition mechanism.

1. Introduction

NASA and ISAS have agreed in principle to collaborate on the ISAS MUSES C mission for the mutual benefit of both space agencies. Presently, the collaboration includes the following elements in addition to the existing MUSES C mission. NASA will: 1) build and deliver to ISAS a rover to be used on the surface of the asteroid, 2) provide DSN antenna time for commands, telemetry and navigation, 3) provide navigation support for critical phases of the mission, 4) support the testing and design review of the MUSES C heat shield at facilities of the Ames Research Center, 5) support optical and radio frequency observations of the target in apparitions close to launch, 6) arrange the recovery of the MUSES C sample capsule on US soil and 7) provide co-investigators for the instruments on the MUSES C spacecraft. ISAS will: 1) deliver the NASA rover to the asteroid, 2) provide a mission design that enables a scientifically valuable rover mission, 3) provide information on the sampling mechanism, 4) provide a small portion of the sample material to NASA, 5) allow NASA investigators to analyze the sample material with ISAS colleagues in Japan and 6) provide co-investigators for the instruments on the NASA rover. The ISAS MUSES C mission is fully described in reference 1.

2. MUSES CN Project

NASA has asked JPL to implement the NASA portion of the collaboration on MUSES C. At JPL, the MUSES CN [N for NASA] project has been established for this purpose. At JPL the MUSES CN activities fall into three technical areas: 1) science, 2) mission support and 3) rover development/operations.

The science element has the responsibility to deliver scientific information to NASA and the public from the following three distinct activities: 1) rover science, 2) MUSES C orbiter science and 3) sample science. The MUSES CN science team will perform these duties in cooperation with their Japanese colleges, the rover operations team and the orbiter operations team. The science element of the MUSES CN project extends to 2007 when the NASA portion of the asteroid sample is returned to the US for investigation by NASA scientists. Presently, the MUSES CN science element is supporting NASA in the preparation of the MUSES CN Announcement of Opportunity. Via this AO, NASA will select the science team members for the rover instruments, the co-investigators for the orbiter instruments and one scientist to participate in the selection of the sample sites and initial sample analysis, characterization, curation and division in Japan. The mission support element of the MUSES CN project has the responsibility to implement the following work: 1) sample recovery, 2) DSN interface, 3) navigation, 4) MUSES C heat shield design review and testing and 5) NEPA. NEPA is the National Environmental Policy Act whose requirements must be followed in order to recover the MUSES C sample capsule on US soil. The MUSES CN Navigation support consists of assisting the MUSES C project by providing estimates of the MUSES-C spacecraft orbit (position and velocity) for the following critical mission events: 1) launch and initial acquisition, 2) outbound (earth - asteroid) maneuvers, 3) inbound (asteroid - earth) maneuvers and 4) earth re-entry. The MUSES CN sample recovery element will work with ISAS and USAF to arrange for the MUSES C sample recovery capsule (SRC) to be targeted for Earth re-entry such that the SRC lands at the proposed landing site [Utah Test and Training Range (UTTR)] with an acceptable maximum ground landing footprint. The MUSES C SRC landing must also be consistent with the NASA Planetary Protection requirements. The MUSES-CN mission and system engineering support is responsible for ensuring that the project capabilities meet the project requirements via working through various mission scenarios. These scenarios will be documented in the MUSES-CN Mission Plan.

3. MUSES-CN Mission

The MUSES-CN rover mission begins when it (Figure 1) is ejected from the MUSES-C spacecraft onto Nereus. Prior to release, the solar-powered rover sits inside the Orbiter-Mounted Rover Equipment (OMRE). While attached to the spacecraft, the rover is shielded from the Sun. The OMRE is the rover's interface to the spacecraft and contains an antenna/ receiver for rover- OMRE communication and a data line for data transfer. The rover will uplink at least 8 Mb of data a day to the spacecraft; these science and engineering data and will be compressed appropriately in consultation with the engineering and science teams. The MUSES-C spacecraft will downlink at least 8 Mb of rover data a day to Earth.

Once the rover is dropped from the spacecraft, it is expected to bounce a few times before coming to rest on the surface. It will then orient itself. Due to the low-gravity environment, the maximum speed the rover can travel is about 1.5 mm/sec without losing surface contact. The rover has been designed with the capability to right itself if it flips onto its back. Since the four posable struts are independent, the rover can

Table 1. Nominal Asteroid Parameters

Property	Nereus	1989 ML
Absolute Magnitude	18.5	19.5
Albedo Limits	0.04 - 0.15	0.04 - 0.15
Effective Radius (km)	0.3 - 0.7	0.2 - 0.4
Bulk Density (g/ cc)	1 - 4	1 - 4
Rotation Period (hrs)	15.2	> 4
Spectral Class	C, F, or EMP	C (uncertain)
Escape Velocity (m/sec)	0.22 - 1.05	0.15 - 0.60
Surface Velocity (cm/sec^2)	(0.8 - 8.0)x10^{-2}	(0.6 - 5.0)x10^{-2}
Perihelion (AU)	0.95	1.10
Aphelion (AU)	2.03	1.45
Orbital Period (yrs)	1.82	1.44

Table 2. Mission Operations at Nereus (2003)

MUSES-C Mission Phase	Nominal Dates	Stay Time Wk.	Sun Range (AU)	Nereus Range (km)
Initial Acquisition and Margin	April 6 - April 20	2	1.85	20 - 50
Mapping	April 21 - May 5	2	1.8	20
Sampling and Rover Deployment	May 6 - May 20	2	1.75	0 - 20
Extended Science	May 21 - May 29	1	1.7	0 - 20
Leave Nereus	May 30		1.66	----

Figure 1. MUSES-CN Rover

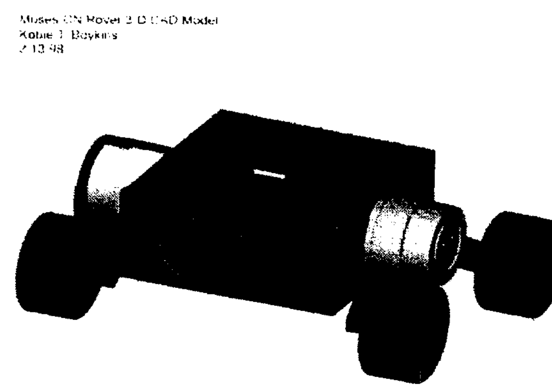
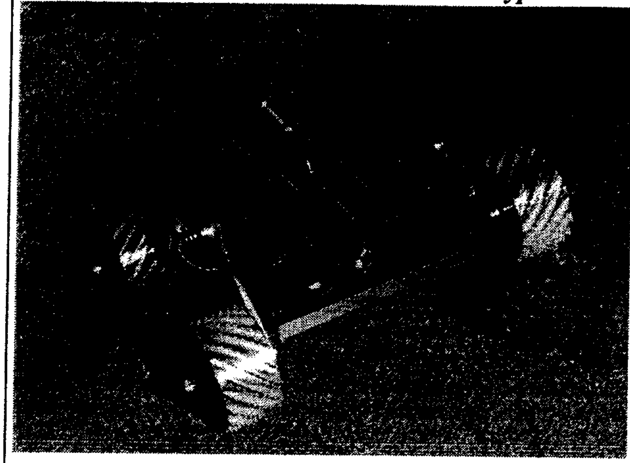


Figure 2. MUSES CN Rover Prototype



be commanded to point itself in any orientation. A pointable mirror and actuated focus mechanism allow the rover to take panoramic images as well as microscopic ones.

The primary rover science objectives are to carry out scientific measurements with its entire instrument suite and to transmit the data before asteroid "night," at which time, the rover will shut down until sunrise. There is little non-volatile storage on the rover. Most data not transmitted to the orbiter at the end of the daily investigation schedule will be lost. Daily investigations include visual imaging of the terrain and targets of interest, point spectra in the infrared, AXS spectra, and soil mechanics investigations using the rover as an instrument.

Understanding the orientation of the rotation axis of the asteroid with respect to the Sun will be critical for rover placement on the surface to ensure maximum operational periods. As a technology experiment, the rover is being designed with the capability to "hop" in low-gravity. If the experiment is successful, the rover may be able to transverse long distances [10 - 100 m's]. This behavior may enable the rover to stay in the Sun longer to take more data and avoid thermal cycling. The rover will try to reach and look inside one or more of the craters left by a sampling event to ascertain stratigraphy which will be lost in the collected sample. The rover will also seek evidence for sample modifications due to the impact process. The nominal rover mission ends when the orbiter departs Nereus. As a technology experiment, the rover may include an experimental optical communications capability. This capability, if implemented, may enable low-rate communications between the rover and Earth after the departure of the MUSES-C spacecraft until the demise of the rover.

The MUSES CN rover will be a direct descendant of the technology used to build the Sojourner rover used on the Mars Pathfinder mission, while being 20 times less massive and including more capability for scientific measurements. The total mass allocated by ISAS for the NASA payload is only a little more than 1 kg. The MUSES CN rover is an experiment of rover mobility and miniaturization first and an enabler of science measurements second. This order of objectives is also similar to the Pathfinder Sojourner rover.

The key rover characteristics are listed in tables 3 and 4. The rover can communicate as long as it is powered and has a direct line-of-sight to the spacecraft.

Table 3 Rover Characteristics

Rover Characteristic	Value
Mass	800 grams
Size	14 x 14 x 6 cm
Power	2.9 W (normal incidence)
Max. velocity, rolling contact in microgravity	1.5 mm/ sec
Data rate	up to 38.4 kbits/ sec, as low as 2.4 KBPS

The rover consists of a rectangular body, which is 14x14x6 cm in dimension with four wheels on four posable struts for mobility (see Figure 2). The wheels are 6.5 cm in diameter, mounted on struts, which extend in pairs from hubs emerging from the geometric center of two opposing 14x6 cm faces of the body. Each strut is 7 cm long from the center of their pivot to the center of the wheel axis. Each of the six faces of the rover body has solar cells so that some power can be generated when the rover is illuminated by the sun from any angle. The top face will deliver 2.9 Watts oriented at 45 degrees to the sun vector at 1.12 AU from the Sun. The top face also has the elements needed to transmit the radio signal.

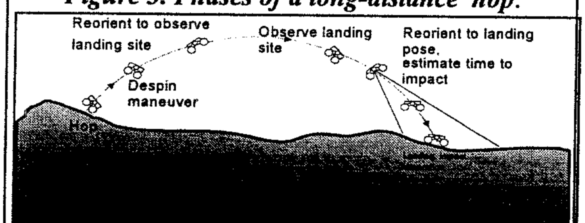
Each exterior face has the solar panel mounted on its corresponding substrate. The solar panels will stay near radiative equilibrium with the sky and thus range from 115 C at local noon to about -155 C just before sunrise.

The thermal operating range of the instruments is -80 C to 30 C.

Table 4 MUSES-CN Instruments

Instrument	Capability
Panoramic and Near-Imaging Camera	• 512x512 (minimum 256 x 256)Active Pixel Sensor, 11.9 micron pixels (max 20 micron) • two(or three)-position focus camera with a scannable mirror to find spots in focus • 8-position filter wheel(6 for science)
Near-Infrared Spectrometer	• 0.9 - 1.7 mm spectral range • spectral resolution <20 (expect 5)nm
Alpha X-ray Spectrometer	• measures elemental abundances of surface soils and rocks

Figure 3. Phases of a long-distance hop.



All instruments will fit inside the rover body. There will be a view window on the front face for the camera and IR spectrometer. The AXS sensor will open out to the rear of the rover and be placed in contact with rock or regolith by appropriate body/strut motion.

The mobility subsystem of the rover (the four wheels, four struts) is designed to support nominal mobility and body-pose functions in full Earth gravity for testing and also designed to enable significant hops in the expected worst-case microgravity environment of 8 to 80 μg of surface acceleration and an escape velocity of about 15 -105 cm/ sec. The rover mobility system will maintain the mechanical configuration of the rover if power is lost.

The surface gravity on Nereus is expected to be 8 to 80 μg and the escape velocity will be 0.2 to 1 m/s. With this low gravity, the gravitational force on an 800-gram rover would be less than 0.08 grams of force. Depending on the model used for the surface properties of the asteroid, this low, normal force could imply certain mobility problems for conventional wheeled vehicles. If the surface is modeled as having conventional friction (e.g. coulombic friction), then the mobility characteristics of a vehicle in the asteroid environment will be a slow-motion version of the dynamics of an off-road vehicle on Earth. If the vehicle hits a 0.5 cm bump on the surface of the asteroid, computer simulations show that it will go more than one vehicle length into the sky and frequently overturn. For this reason, as well as the desire to be ejected from the host spacecraft at an altitude of a few tens of meters, the rover has been designed to be self-righting and to be able to operate upside down. The concussion of hitting the surface at 1 cm/sec or after falling from 10s of meters of height is no more than falling a few millimeters on Earth.

For longer-range mobility, hopping is planned. A brief description of a long-distance hop (see Figure 3) will help to identify some of the inherent technical challenges.

For precise motion of the rover to nearby target locations, the rover will roll slowly. For a wheel radius of 3 cm and a surface acceleration of 20 microgees the corresponding velocity is 2.3 mm/sec.

Each strut/wheel assembly will also include a sensor to infer that the wheel is in contact with the terrain. This sensing will be used to allow the vehicle to roll on four wheels (instead of just three, which would be the natural state for a four-wheel vehicle without a passive suspension), to detect when one of the wheels has encountered an obstacle, to allow the vehicle to "hop" with all four wheels pushing so that no significant angular momentum is induced into the body, and to anticipate contact a fraction of a second before landing at the end of a hop.

Hopping is viewed as an important technology experiment for the rover on the asteroid. Fine positioning of the rover will be accomplished by normal rolling motion at slow speeds of 1.5 millimeters per second or so. At these speeds it is believed that the gravity force (20 microgee nominal) and other forces (e.g. Van der Waal's, electrostatic) will allow the rover to maintain at least two wheels in contact with the terrain at all times. With contact sensing, the odometry for those wheels which are instantaneously in contact should be quite accurate (~5%). This accurate odometry, together with heading information derived from the sun will allow relatively precise, but slow, motion to selected targets on the surface. For longer-range motion, hopping is essential. Hops at up to 20 cm/sec will permit vertical motions of hundreds of meters and horizontal motions up to 1 asteroid radius. Control of the body pose during the hop will allow mosaic imaging during this relatively slow maneuver (e.g. 40 minutes) as well as an estimation of the time and place of impact, and the surface topography near the landing site. Control of the body pose and actuation of the struts and wheels just before and during the time of contact will allow impact energy absorption, preventing long bounces.

The Orbiter-Mounted Rover Equipment (OMRE) will be a rectangular boxes approximately 30x30x15cm. The OMRE has the following functions: 1) thermal control of the rover during cruise, 2) mounting the rover to the spacecraft during launch and cruise, 3) ejecting the rover off the spacecraft at the asteroid, 4) transmitting commands from the orbiter to the rover, 4) receiving data from the rover and transmitting it to the orbiter for re-play to Earth and 6) housing OMRE computer.

4. Summary

NASA and ISAS are committed to collaboration on the ISAS MUSES C mission. The collaboration significantly benefits both space agencies. The collaboration includes science, mission support and hardware delivery/operations. ISAS's MUSES C mission is the first asteroid sample return mission and NASA's MUSES CN mission is the first mission to operate a vehicle in the micro gravity environment of a small body. The MUSES CN rover will be 20 times less massive that the Pathfinder Sojourner rover and will carry more science instruments. The MUSES CN rover will be able to roll, hop and right itself in the micro gravity environment of an asteroid.

Both the MUSES C and MUSES CN missions have aggressive technology demonstration objectives as well as enabling many important science investigations into the nature and origin of asteroids, the most important of which is the acquisition and return to Earth of a sample of a near Earth asteroid. In addition to the technology and science aspects of the missions, it is anticipated that the MUSES C and MUSES CN missions will attract a good deal of attention from the public and media in both countries. The extensive collaboration between NASA and ISAS on MUSES C will provide experiences upon which both space agencies can build for future possible collaborations on planetary missions.

The MUSES C spacecraft design is now at the final period of prototype model phase, which will be closely followed by the Flight Model fabrication beginning in 1999. The MUSES CN project has just performed its Preliminary Design Review and is entering an intensive design period leading to the Critical Design Review at the end of 1998. Both projects include a large number of new engineering advances, which have a significant amount of development and operations risk. Both projects are working hard to manage the risk and deliver the promised technology and science results. The projects are fortunate to have a backup target, 1989 ML, whose launch window is open in July of 2002, half a year later, which still maintains the mission duration of four years and returns the sample to the Earth in 2006.

References

[1] Kawaguchi, J. et. al, "The MUSES C, Mission Description and its Status", Third IAA International Conference on Low-Cost Planetary Missions, April 27 - May 1, 1998, Jet Propulsion Laboratory, Pasadena California.

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